2 MINERνA Physics Goals and Detector Design Drivers

2.5 The Perturbative and Non-Perturbative Interface

2.5.1 Quark Distributions at Large x

One of the most fundamental properties of the nucleon is the structure of its valence quark distributions. Valence quarks are the irreducible kernel of each hadron, responsible for its charge, baryon number and other macroscopic properties. Sea quarks, which at high Q^2 are largely generated through gluon bremsstrahlung and subsequent splitting into quark-antiquark pairs, represent one source of the non-perturbative dressing of the valence quarks at low Q^2. At higher x values these quark / anti-quark contributions drop away, and the physics of the valence quarks is cleanly exposed. Although a large body of structure function data exists over a wide range of x and Q^2, the region $x > 0.6$ is not well explored.

Knowledge of the valence quark distributions of the nucleon at large x is vital for several reasons. Measurements of structure functions at large x will bring insights into the mechanisms responsible for spin-flavor symmetry breaking. In addition, quark distributions at large x are a crucial input for estimating backgrounds in searches for new physics beyond the Standard Model at high energy colliders [1].

The uncertainties in the current nucleon parton distribution functions at high x are of two predominant types: the ratio of the light quark pdf's, $d(x)/u(x)$, as $x \to 1$ and the role of leading power corrections (higher twist) in the extraction of the high x behavior of the quarks. The measurement of quark densities at high-x_{Bj} is closely related to the question of the leading power corrections known as "higher twist effects". The n^{th} order higher twist effects are proportional to $1/Q^{2n}$ and reflect the fact that quarks have transverse momentum within the nucleon and that the probe becomes larger as Q^2 decreases, thus increasing the probability of multi-quark participation in an interaction. Different analyses of higher twist corrections in current data leave some unresolved issues that would benefit from new experimental information.

The only actual measurements of a higher-twist term in neutrino experiments have been two low-statistics bubble chamber experiments: in Gargamelle [2] with freon and in BEBC [3] with NeH_2. Both bubble chamber analyses are complicated by nuclear corrections at high-x. However, both analyses found a twist-4 contribution that is smaller in magnitude than the charged leptoproduction analysis and, most significantly, is preferentially negative.

Higher twist components of the structure functions may be obtained from deviations of measured data from the calculable expectations from perturbative QCD. As shown in Figure 1, the expected structure function MINERνA uncertainties will be such that this type of higher twist analysis may be performed precisely for the first time with neutrino measurements. In this case, it is crucial also to understand the effects arising from nuclear medium modifications to the nucleon structure functions, which will also be measured by MINERνA.

2.5.2 Quark-Hadron Duality

The description of hadrons in terms of their fundamental quark and gluon constituents is one of the major challenges in nuclear physics today. While at present we cannot describe the structure and interactions of hadrons directly utilizing the quark and gluon degrees of freedom of QCD, we know that in principle it should just be a matter of convenience in choosing to describe a process in terms of quark-

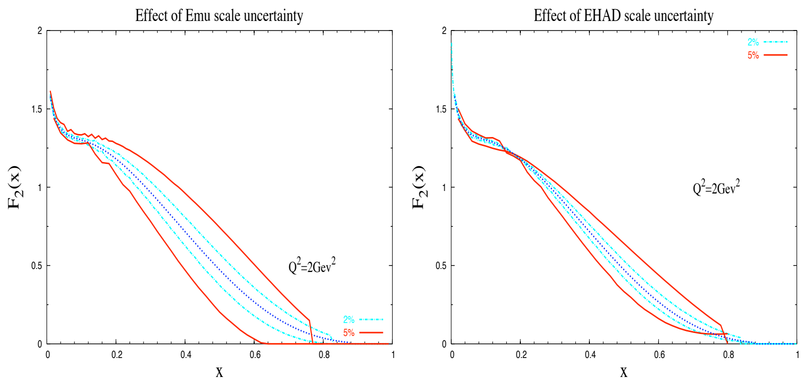

Figure 1: The effect of the (dominant) energy scale uncertainties. muon on left and hadron on right, on the x dependence of the F_2 structure function is shown for the transition region at at $Q^2 = 2$ GeV^2. Here, for instance, x = 0.7 corresponds to $W^2 = 1.7$ GeV^2 in the resonance region.

gluon or hadronic degrees of freedom. This fact is referred to as *quark-hadron duality*, and means that one can use either set of complete basis states to describe physical phenomena. At high energies, where the interactions between quarks and gluons become weak and quarks can be considered asymptotically free, an efficient description of phenomena is afforded in terms of quarks; at low energies, where the effects of confinement make strongly-coupled QCD highly non-perturbative and the final state is guaranteed to be made of hadrons, it is more efficient to work in terms of collective degrees of freedom, the physical mesons and baryons. The duality between quark and hadron descriptions reflects the relationship between confinement and asymptotic freedom, and is intimately related to the nature of the transition from non-perturbative to perturbative QCD. It has been said that (short of the full solution of QCD) understanding and controlling the accuracy of the quark-hadron duality is one of the most important and challenging problems for QCD practitioners today [4].

Although the duality between quark and hadron descriptions is formally exact in principle, how this reveals itself specifically in different physical processes and under different kinematical conditions is a key to understanding the consequences of QCD for hadronic structure. The phenomenon of duality is in fact quite general in nature and can be studied in a variety of processes, such as $e^+e^- \rightarrow$ hadrons, or semi-leptonic decays of heavy quarks. Duality in lepton–nucleon scattering, historically called Bloom-Gilman duality, links the physics of resonance production to the physics of deep inelastic scaling. Duality is manifested here in the observation that the hadronic (resonance) and quark (scaling) strengths are, on average, equivalent. Moreover, this is true for all Q^2 observed above $Q^2 \approx 1$ GeV^2, and thus a perturbative behavior apparently describes the average Q^2 dependence of the hadronic, non-perturbative, resonance enhancement region.

The proposed MINERνA experiment is uniquely poised to provide a wealth of data to answer where duality works, in what structure functions, in what reactions, and at what kinematics. Duality has been well-verified [6] for the proton F_2 structure function [7], observed recently in the separated longitudinal and transverse unpolarized structure functions [8], on nucleons and in nuclei [9], and in polarized structure functions [10]. While it's fundamental cause remains a mystery, duality appears experimentally to be a non-trivial property of nucleon structure. It is, therefore, crucial to test it in a variety of reactions – including neutrino-nucleon and nucleus scattering and the structure function xF_3.To accomplish such a study, high precision structure function data are needed in both the deep inelastic and in the resonance regimes. As can be seen in Figure 2, MINERνA will have high statistics in both of these regions.

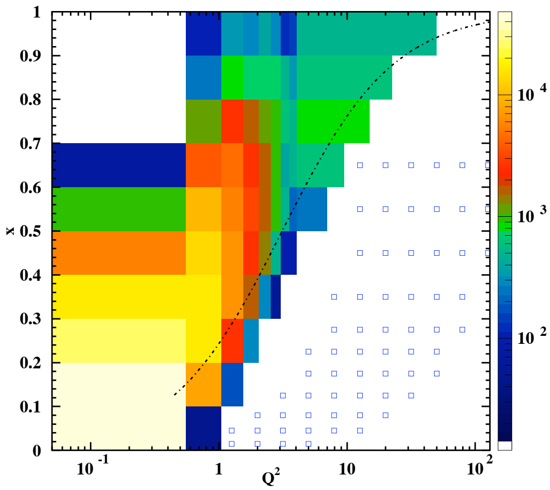

Figure 2: Available xF_3 data (open symbols) and the anticipated (resonance region) MINERνA data (colored distributions in x and Q^2. The curve indicates the commonly-utilized $W^2 = 4\,\mathrm{GeV}^2$ boundary between the deep inelastic and resonance regimes. The color key to the right indicates anticipated MINERνA statistics.

Duality studies of electron-deuteron scattering at low Q^2 reported a resemblance to deep inelastic neutrino-nucleus scattering at much higher Q^2, indicating a potential sensitivity of duality to the valence quarks [11]. The proposed experiment will allow this observation to be verified and tested for the first time, as data from like kinematic regimes but differing in probe and interaction (from MINERνA and Jefferson Lab) may be compared directly. As shown in Figure 3, the kinematic regimes of these facilities are quite complementary.

2.5.3 QCD Moments

Figure 3 depicts the substantial kinematic range enhancement in both x and Q^2 made possible by the MINERνA experiment. This broad range of the data will allow for accurate moments of the structure functions to be obtained. To obtain a structure function moment, it is necessary to integrate over the full range in x at a fixed value of Q^2. These moments are fundamental quantities, calculable in QCD and recently calculated in lattice QCD at $Q^2 = 4\,\mathrm{GeV}^2$ for valence distributions [13]. If duality is shown to hold, the proposed data may provide one of the few available quantities which can be directly compared to lattice QCD calculations - that is, a valence-only structure function moment.

As can be seen in Figure 3, at $Q^2 = 4\,\mathrm{GeV}^2$, MINERνA will measure the entire range $0.00005 < x < 1$, allowing for moments to be obtained with about a 5% precision. It is important to note two things in this case - first, nuclear effects are not expected to play a role in the integrated moments,

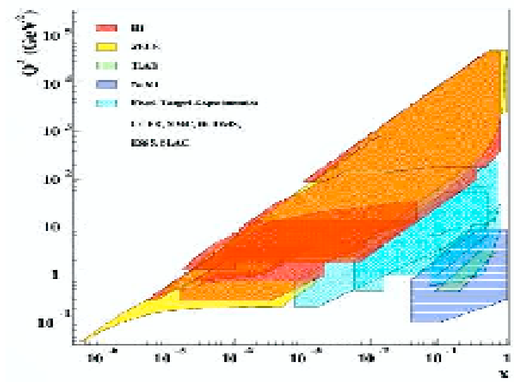

Figure 3: Kinematic coverage of existing and anticipated structure function measurements.

as it has been shown that the momentum sum rule is preserved in nuclei [14]. Next, uncertainties in kinematics play only a reduced role in moment extractions, which are integrated in x, or in W^2.

Large x (resonance region) data become increasingly important for higher order moments. At n=6, for example, the resonance and large x region above $x = 0.7$ make up 70% of the Cornwall-Norton moment of F_2 at $Q^2 = 10$ (GeV/c)^2. The contribution is larger at $Q^2 = 4$ GeV^2, where lattice calculations are available. As noted above and clear in Figure 2, there currently exist little to no neutrino resonance cross section data in the resonance region or at larger x, while such data which will be easily obtainable with MINERνA.

References

[1] S. Kuhlmann *et al.*, Phys. Lett. B **476**, 291 (2000).

[2] H. Deden and et al., [Gargamelle Neutrino Collaboration], "Experimental Study Of Structure Functions And Sum Rules In Charge Changing Interactions Of Neutrinos And Anti-Neutrinos On Nucleons," Nucl. Phys. **B85**, 269 (1975).

[3] K. Varvell *et al.* [BEBC WA59 Collaboration], Z. Phys. C **36**, 1 (1987)

[4] M. Shifman, Handbook of QCD, Volume 3, 1451, World Scientific (2001)

[5] F. E. Close and N. Isgur, Phys. Lett. B **509**, 81 (2001)

[6] W. Melnitchouk, R. Ent and C. Keppel, Phys. Rept. **406**, 127 (2005) [arXiv:hep-ph/0501217].

[7] I. Niculescu *et al.*, Phys. Rev. Lett. **85**, 1186 (2000)

[8] C. E. Keppel, *Prepared for Exclusive Processes at High Momentum Transfer, Newport News, Virginia, 15-18 May 2002*

[9] J. Arrington, R. Ent, C. E. Keppel, J. Mammei and I. Niculescu, arXiv:nucl-ex/0307012 (submitted to Phys. Rev. Lett.)

[10] A. Fantoni [HERMES Collaboration], periment," Eur. Phys. J. A **17**, 385 (2003).

[11] I. Niculescu *et al.*, Phys. Rev. Lett. **85**, 1182 (2000).

[12] A. Bodek and U. K. Yang, arXiv:hep-ex/0203009.

[13] D. Dolgov *et al.* [LHPC collaboration], e QCD," Phys. Rev. D **66**, 034506 (2002) [arXiv:hep-lat/0201021].

[14] I. Niculescu, J. Arrington, R. Ent and C. E. Keppel, Phys. Rev. C **73**, 045206 (2006) [arXiv:hep-ph/0509241].